

## Improvement in Knee Extension Strength through Training by Means of Combined Electrical Stimulation and Voluntary Muscle Contraction

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IWASAKI, T., SHIBA, N., MATSUSE, H., NAGO, T., UMEZU, Y., TAGAWA, Y., NAGATA, K. and BASFORD, J.R. *Improvement in Knee Extension Strength through Training by Means of Combined Electrical Stimulation and Voluntary Muscle Contraction.* Tohoku J. Exp. Med., 2006, **209** (1), 33-40 — Weight training (WT) is the most common method of maintaining and increasing muscle strength. WT, however, is not always useful as it requires the external resistance and stabilization. We have developed a “hybrid training” (HYB) approach that avoids these problems by using electrically stimulated muscles to provide resistance to the motion of a muscle undergoing training. Here we report the efficacy of HYB compared with conventional WT for increasing the muscle strength around the knee at both slow and fast joint speeds (at 30 and 180°/sec). Two matched groups, each of 8 healthy men aged 22 years, exercised 3 times/week for six weeks. Both groups showed significantly increased strength in concentric torque at 30°/sec (HYB +28%, WT +33%) and at 180°/sec (HYB +33%, WT +38%), and also in eccentric torque at 30°/sec (HYB +25%, WT +24%) and at 180°/sec (HYB +19%, WT +30%) ( $p < 0.001$ ). HYB is comparable with WT exercising with the exception of high-speed contractions, while HYB has a clear advantage in not needing external resistance equipment or stabilization. HYB is therefore considered a useful approach for strengthening muscles when a person is restricted to bed rest or during space flight. ——— rehabilitation; exercise; electrical stimulation; knee extension; strength

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Exercise is essential in the maintenance of health and strength. Current approaches with weights and resistance devices are effective and are capable of increasing the strength of sedentary or de-conditioned people by 25 to 100% over a

period as short as a few months (Fiatarone et al. 1994; Rall et al. 1996; Kuge et al. 2005). However, conventional weight training (WT) is not feasible and an alternative is needed when a person is restricted to bed rest or during space

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flight. An alternative approach using electrical stimulation (ES) is already used to a limited extent to strengthen immobilized and paralytic muscles (Balogun et al. 1993; Stein et al. 1999). ES, unfortunately, suffers from a number of limitations, which include nonphysiological recruitment patterns that preferentially favor fast twitch (Type 2) fibers (Chilibeck et al. 1999). Those muscles are located near the stimulating electrodes. Another issue that may be particularly important for training to higher levels of function is that ES strengthening typically does not utilize the reciprocal limb movements that are involved in the activities of everyday life.

We have developed a hybrid exercise (HYB) designed to overcome these limitations by using the force generated by an electrically stimulated muscle to resist the motion of its volitionally contracting agonist (Yanagi et al. 2003). This method has the benefits of utilizing more normal muscle recruitment patterns than are possible with conventional ES programs while at the same time minimizing the need for external stabilization and resistance apparatus required by conventional WT. This approach has been shown to be capable of increasing elbow extension torque by about 30% and proximal upper extremity muscle cross-sectional areas by about 15% over a 12-week period (Yanagi et al. 2003). However, the applicability and effectiveness of this method to the strengthening of the larger and stronger muscles of the lower extremities are unknown. The present study was designed to address this deficiency by comparing the torque production of HYB and WT program on eccentric and concentric knee extension.

## METHODS

This protocol was approved by the Internal Review Board (IRB) of Kurume University. Following approval, informed consent was obtained from 16 healthy sedentary men who had reviewed the goals of the study and agreed to participate. The subjects were instructed to avoid participation in new strenuous or sports activities. They were also required to have normal musculoskeletal function (i.e., normal strength, sensation, coordination, and range of motion) and to be either naïve to WT

or, not to have participated in WT for at least a year. The 16 qualifying subjects were then randomly divided into 2 groups of 8 with the only difference between the groups being that one began the HYB program of both lower extremities while the other began a WT regimen.

The demographics of the groups did not differ in any statistically significant manner. The mean age of the HYB group subjects was 22.3 (range 20 to 26) years, and their mean weight was  $61.40 \pm 10.51$  kg. The corresponding values for these quantities in the isotonic WT control group were 21.8 (range 19 to 26) years and  $64.79 \pm 9.11$  kg, respectively. All subjects attended all training and evaluation sessions.

## Exercise

Training occurred 3 times a week (Monday, Wednesday, and Friday) for 6 weeks. Each session consisted of 10 sets of 10 reciprocal 2-sec ( $45^\circ/\text{sec}$ ) knee flexion and extension contractions with 15 repetition maximum (15-RM) loads (equivalent to 65 - 70% of 1RM) (Ishii 2002; Kraemer et al. 2002). Sets were separated by 1-min rest intervals, and an exercise session involving both lower extremities required 15 min and 40 sec to complete (Yanagi et al. 2003).

*HYB.* Exercises were performed with the subject sitting erect in a chair with his hamstrings electrically stimulated as he volitionally extended his knee and his quadriceps stimulated as he volitionally bent flexed his knee (see stimulation protocol below). The joint range of motion was restricted to a  $90^\circ$  arc that extended from  $10$  to  $100^\circ$  ( $0^\circ$  indicating full knee extension) (Fig. 1).

*Electrical stimulation device.* The electrical stimulation device has been described previously (Ogino et al. 2002; Yanagi et al. 2003) and consists of a custom designed waveform generator capable of delivering stimulating signals with unique frequencies and waveforms to as many as 8 pairs of electrodes. Pairs of  $2 \times 6$ -cm electrodes (NIHON MEDIX Co., Chiba) were placed over the motor points of the quadriceps and hamstrings that had been isolated with the electrical stimulation device used in this study on the basis of having the lowest transcutaneous muscle stimulation thresholds.

*Stimulation parameters.* The stimulation waveform used in this study is similar in some ways to that of "Russian stimulation" (Ward and Shkuratova 2002) and consisted of a 5,000 Hz carrier frequency modulated at 20 Hz (2.4 ms on, 47.6 ms off) to deliver a rectangular biphasic pulse (Ogino et al. 2002; Yanagi et al. 2003).

Maximum comfortable stimulation intensities were

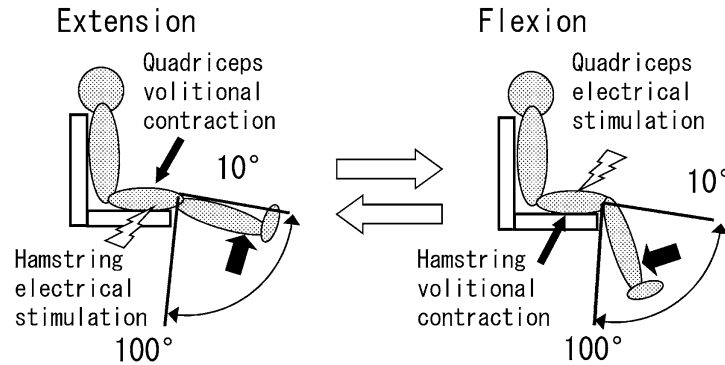


Fig. 1. Schematic model of HYB. Subjects sat on a chair, with their quadriceps stimulated as they attempted to bend their knee and their hamstrings stimulated as they attempted to extend it (see methods section).

determined one month before the training period began in a manner that has been previously described (Yanagi et al. 2003). Stimulation intensities (all less than the maximal comfortable values determined above) were adjusted to permit the subjects to perform 15 - 20 consecutive knee flexion and extension contractions. The mean stimulating voltages were  $50.46 \pm 9.01$  V (range 32.61 - 61.49 V) and  $44.79 \pm 9.22$  V (range 27.43 - 55.58 V) for the quadriceps femoris and hamstring muscles, respectively. The output powers were  $< 10$  W, and current intensities were  $< 10$  mA/cm<sup>2</sup>.

*WT.* Training was performed in a manner analogous to that of the HYB group. Baseline measurements were obtained one month before training began. However in this case, 1-RM loads were determined throughout the flexion/extension range of motion with a weight-based exercise machine (SAKAI Medical Co., Tokyo), and approximately 67% of these loads were then used in training to correspond with the 15 RM loads of the HYB group (Ishii 2002; Kraemer et al. 2002).

#### *Torque measurements*

Maximal volitional isokinetic eccentric and concentric knee extension torques were measured at angular velocities of 30° and 180°/sec with a KIN-COM (Chattanooga Group Inc., Hixson, TN, USA) as the subjects sat strapped in a chair. Each session began by establishing that the subject could move his lower extremity comfortably throughout the full 10 - 100° arc of the exercise range. The subject then performed three practice contractions in the direction, and at the speed, to be tested. Torques were determined sequentially in the following order: 30°/sec concentric, 30°/sec eccentric, 180°/sec concentric, and 180°/sec eccentric contraction,

with 5-min rest periods between each measurement. Each session consisted of 3 sets of measurements for each velocity and contraction type, separated by 3-min rest intervals; the three measurements at each speed and contraction type from both lower extremities were pooled, and the mean used in the data analysis. Torque production measurements were made at a baseline session within a week of the start of the study as well as at its 3-week midpoint, its 6-week conclusion, and afterward at follow-up 4 weeks later. Subjects were released from their restrictions against beginning new or strenuous activities (see above) at the end of the 4-week follow-up period.

#### *Statistics*

Torque production measures were obtained for subjects within their groups at baseline, 3-week, 6-week, and follow-up evaluations and were analyzed using one-way repeated measures analysis of variance (ANOVA). When a significant difference was found, *post hoc* comparisons were performed using a Bonferroni correction. Student's *t*-test was performed to compare the torque production between groups at each measurement period. All statistical analyses were performed using SAS (SAS Institute Inc., Cary, NC, USA). Statistical significance was accepted for the level of  $< 0.05$ .

## **RESULTS**

### *Muscle Force Measurement*

#### *Concentric knee extension torque*

*HYB group.* The maximal concentric knee extension torques of the HYB group (Table 1, Figs. 2a and 2b) increased by 22% ( $p < 0.001$ ) at

30°/sec and 26% ( $p < 0.001$ ) at 180°/sec at the 3-week midpoint of training. These values further increased to 28% ( $p < 0.001$ ) and 33% ( $p < 0.001$ ) at the end of training and remained elevated above their baseline values at follow-up four weeks later (22% [ $p < 0.001$ ] and 31% [ $p < 0.001$ ]) (ANOVA,  $p < 0.001$ ).

**WT group.** The maximal concentric knee extension torques of the WT group increased 17% ( $p < 0.005$ ) at 30°/sec and 18% ( $p < 0.001$ ) at 180° sec at the 3 - week midpoint of training. These increases continued with time and were 29% ( $p < 0.001$ ) and 38% ( $p < 0.001$ ) respectively at the end of training. These torques remained elevated (20% ( $p < 0.005$ ) and 24% ( $p < 0.001$ ), respectively) above baseline at the 4-week follow-up evaluation (Table 1, Figs. 2a and 2b) (ANOVA,  $p < 0.001$ ).

**Comparison of HYB and WT groups.** Between group analysis revealed that concentric contraction torque improvements did not differ between the groups except at the end of training

at 180°/sec where the WT group was significantly stronger than the HYB group ( $p < 0.05$ ).

#### *Eccentric knee extension torque*

**HYB group.** Gains of maximal eccentric extension torque of the HYB exercise group at the 3 - week midpoint of training (12% at 30°/sec and 8% at 180°/sec) were not statistically significant. Torque production, however, continued to rise with time and had increased in a statistically significant manner to 25% ( $p < 0.001$ ) and 19% ( $p < 0.001$ ) respectively at the end of training. These elevations declined but persisted at follow-up four weeks later 13% ( $p < 0.001$ ) and 5% (n.s.), respectively (Table 1, Figs. 3a and 3b) (ANOVA,  $p < 0.001$ ).

**WT group.** The maximal eccentric extension torques of the WT group increased 18% ( $p < 0.005$ ) at 30°/sec and 14% ( $p < 0.001$ ) at 180° /sec, respectively at the midpoint of training. These values further increased by 24% ( $p < 0.001$ ) and 30% ( $p < 0.001$ ) respectively at the end of the

TABLE 1. *Knee extension torque before and after exercise*

Nm (mean ± S.D.)		Before	3 wks	6 wks	4 wks after
Con 30°/sec	HYB	73.19 ± 19.25	89.13 ± 12.80****	93.44 ± 11.22****	89.00 ± 14.98****
	WT	78.93 ± 21.60	92.57 ± 16.04***	101.93 ± 13.99****	94.43 ± 17.45***
Con 180°/sec	HYB	54.14 ± 7.81	68.14 ± 6.80****	71.79 ± 5.98****	70.93 ± 6.89****
	WT	57.21 ± 14.08	67.57 ± 11.01****	79.07 ± 6.35****	70.86 ± 14.09****
Ecc 30°/sec	HYB	92.44 ± 23.24	103.25 ± 20.64	115.63 ± 12.39****	109.06 ± 17.11****
	WT	95.21 ± 19.34	111.86 ± 12.97***	118.00 ± 16.85****	112.93 ± 24.88*
Ecc 180°/sec	HYB	84.50 ± 19.91	90.94 ± 12.45	100.19 ± 12.29****	88.88 ± 14.82
	WT	85.36 ± 17.84	97.43 ± 14.61****	111.07 ± 14.74****	94.86 ± 19.96*

\* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.005$ , \*\*\*\* $p < 0.001$ .

Con, concentric; Ecc, eccentric.

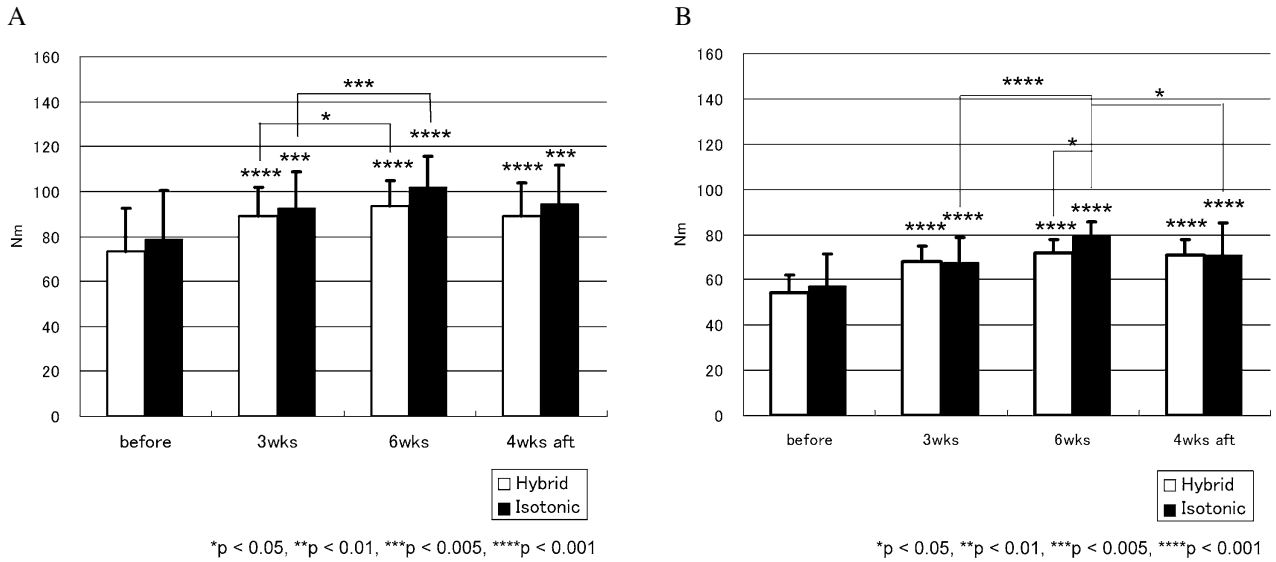


Fig. 2. Concentric knee extension torque (Nm) measurements at baseline at the beginning of the exercise period, its 3-week midpoint, its conclusion at 6 weeks, and at follow-up 4 weeks later. The details of these changes are discussed in the text. However, it is useful to note that the measurements in the HYB and WT groups exhibited similar patterns of improvement in that they increased throughout training and tended to lessen but remain elevated at follow-up. Unless otherwise indicated, *p* values refer to differences of measurement from baseline.

A: 30°/sec.  
B: 180°/sec.

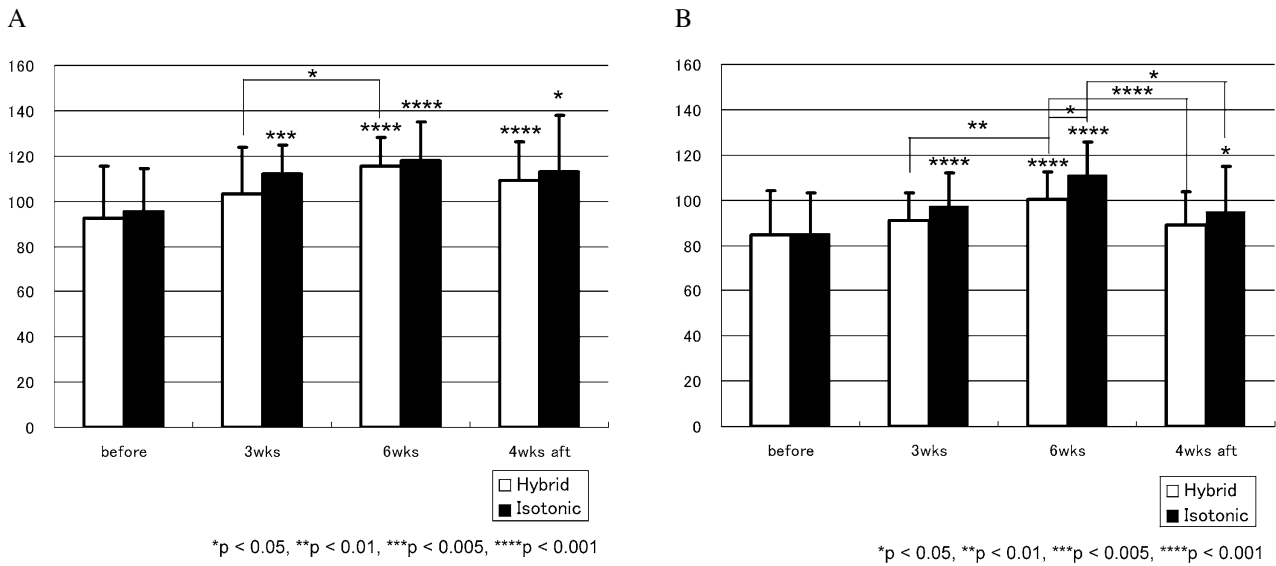


Fig. 3. Eccentric knee extension torque (Nm) measurements obtained at baseline at baseline at the beginning of the exercise period, its 3-week midpoint, its conclusion at 6 weeks, and at follow-up 4 weeks later. The details of these changes are discussed in the text. However, it is useful to note that HYB and WT groups exhibited similar patterns of improvement in that their strength increased throughout training but tended to lessen but remain elevated at follow-up. Unless otherwise indicated, *p* values refer to differences of measurement from baseline.

A: 30°/sec.  
B: 180°/sec.

training period. These values remained elevated (19% [ $p < 0.05$ ] and 11% [ $p < 0.05$ ]) at follow-up four weeks later but were returning towards their baseline values. (Table 1, Figs. 3a and 3b) (ANOVA,  $p < 0.001$ ).

#### *Comparison of HYB and WT groups.*

Between group analysis revealed that eccentric contraction torque production improvements did not differ between the groups except at the end of training at 180°/sec where the WT group was significantly stronger than the HYB group ( $p < 0.05$ ).

### DISCUSSION

This experiment had the goals of determining whether the HYB approach (Yanagi et al. 2003) could be applied to the large muscles of the lower extremities and if so, assessing whether strength gains would be comparable to those obtainable with WT (Ishii 2002; Kraemer et al. 2002). Both goals were met. The subjects tolerated the HYB regimen well; their 19 - 33% improvements in torque production, although less pronounced than those of WT at the higher velocity (180°/sec) testing speed, were not only similar to the 24 - 38% gains of their isotonic counterparts but were also of the same magnitude as 30% gains found previously in the upper extremity (Yanagi et al. 2003). These findings, however, deserve further discussion.

An important issue for our design is that the gains in torque production obtained in both groups of this study were comparable with those reported in the literature. Specifically, while strength gains from exercise intervention trials in trained athletes are typically small (i.e., 5-10%), the 20-40% gains found in un- and “moderately”-trained individuals overlap those of our subjects. Further support for the reasonableness of our findings comes from the fact that while our 6-week training period was shorter than many in the literature (which range in length from 4 weeks to 2 years), the majority of strength gains are known to occur within the first 4 to 8 weeks of an exercise program (Kramer and Fleck 1988; Ishii 2002; Kraemer et al. 2002).

Parameter choice is another important consideration. We chose to study training loads in

the order of 65 - 70% of 1-RM as these forces are accepted as beneficial in producing both muscle hypertrophy and improved endurance (Ishii 2002; Kraemer et al. 2002). Options for higher intensities of electrical stimulation are limited by patient comfort. Future research with an emphasis on muscular endurance might examine the benefits of training at lower loads (perhaps 40 - 60% of 1RM), higher repetition rates ( $> 15$ ), and shorter rest periods ( $< 60$  sec) (Ishii 2002; Kraemer et al. 2002).

We found that torque increases in the two exercise groups were similar to each other at the lower 30°/sec testing velocity and only reached a statistically significant difference (in favor of WT) at the higher speed 180°/sec rate at the end of the training period. It is possible that the velocity-dependent effects of the HYB and WT may differ or that this difference is the result of our choice of 45°/sec as our training velocity. However, this discrepancy occurred at only a single time point and had disappeared at follow-up. Further research will be necessary to explore this issue.

The role of electrical stimulation in strengthening muscles following immobilization and surgery is well known (Talbot et al. 2003; Giorgi et al. 1998; Stein et al. 1999; Stevens et al. 2003; Talbot et al. 2003; Lewek et al. 2004). A recent study has found that several weeks of high intensity ES can improve the strength of normal subjects by 10 - 20% (Hainaut and Duchateau 1992). Our findings support these findings: we found similar but slightly larger 19 - 33% increases in the strength of our subjects undergoing the HYB as well as the conventional WT program.

HYB may have a number of other potential advantages. One of these that has already been mentioned is that HYB involves reciprocal limb movement as well as both concentric and eccentric muscle contractions. As such, it mimics the muscular activity and limb movements that occur during sports and daily life (Kraemer et al. 2002). The presence of an eccentric component may also be beneficial in that these contractions are neuromuscularly more efficient, less metabolically demanding, and more conducive to hypertrophy than concentric contractions (Komi et al. 1987;

Dudley et al. 1991a, b). The fact that an electrically stimulated eccentric contraction requires only about 50% the stimulation intensity of a concentric contraction of similar force (Seger and Thorstensson 2000) may also be important as it allows electrically-assisted eccentric strengthening to occur at lower stimulation intensities than would otherwise be possible.

Another interesting aspect of HYB is that it involves the simultaneous contraction of agonist and antagonist muscles (Fig. 1). As such it is in some ways similar to the simultaneous hamstring and quadriceps contractions of the closed kinetic exercises (CKC) that are central to many rehabilitation programs due to the belief that concurrent activation of opposing muscles can stabilize an injured joint. The significance of this potential benefit is difficult to assess, however, in that recent research may play down the importance of the CKC in knee rehabilitation (Palmitier et al. 1991; Mikkelsen et al. 2000; Beutler et al. 2002). Although it may be slightly less effective at higher velocities, HYB appears comparable to conventional WT in increasing knee extension strength of healthy subjects. HYB may have additional benefits; HYB, unlike conventional WT, does not require the use of external resistance or stabilization. HYB is considered a useful approach for strengthening muscles when a person is restricted to bed rest or during space flight.

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